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REPORT DOCUMENTATION PAGE

AD-A191 590

1b. RESTRICTIVE MARKINGS	
3. DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release; distribution is unlimited.	
4. PERFORMING ORGANIZATION REPORT NUMBER(S)	5. MONITORING ORGANIZATION REPORT NUMBER(S)
6a. NAME OF PERFORMING ORGANIZATION Naval Ocean Systems Center 6b. OFFICE SYMBOL (if applicable) NOSC	7a. NAME OF MONITORING ORGANIZATION Naval Ocean Systems Center
6c. ADDRESS (City, State and ZIP Code) San Diego, California 92152-5000	7b. ADDRESS (City, State and ZIP Code) San Diego, California 92152-5000
8a. NAME OF FUNDING/SPONSORING ORGANIZATION Director of Naval Laboratories 8b. OFFICE SYMBOL (if applicable) DNL	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER
8c. ADDRESS (City, State and ZIP Code) Space and Naval Warfare Systems Command Independent Research Program (IR) Washington, DC 20360	10. SOURCE OF FUNDING NUMBERS PROGRAM ELEMENT NO.: 61152N PROJECT NO.: ZT21 TASK NO.: RR0000 101 AGENCY ACCESSION NO.: DN305 009

11. TITLE (include Security Classification)

RTR Studies of Closed Combustion of Liquid Metal Fuels

12. PERSONAL AUTHOR(S)

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13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
Professional paper	FROM Jun 1987 TO Jul 1987	January 1988	

16. SUPPLEMENTARY NOTATION

17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB-GROUP	Rankine cycle liquid metal combustion cylindrical combustors fuel bath

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

The use of liquid metal combustion as a Rankine cycle heat source in stored chemical energy propulsion systems for undersea vehicles has fostered interest in the fundamental processes occurring during such combustion. This paper reports an investigation into the use of high energy, real-time radiography to provide X-ray images of the confined combustion of an oxidant injected and submerged in a fuel bath. Studies of the combustion processes and fluid dynamics of the jet-driven circulating flow in the fuel bath are described. Results of tests using cylindrical combustors which have single, horizontal oxidizer jets at their centerlines are presented. Selected radiographic images showing some of the large scale, low frequency turbulence, dense product behavior and reaction zone growth which occurs during such closed combustion processes are presented and discussed. Keywords:

Presented at AIAA/SAE/ASME 23rd Joint Propulsion Conference, San Diego, CA; 29 June - 2 July 1987.

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20. DISTRIBUTION/AVAILABILITY OF ABSTRACT ☐ UNCLASSIFIED/UNLIMITED ☒ SAME AS RPT ☐ DTIC USERS	21. ABSTRACT SECURITY CLASSIFICATION UNCLASSIFIED
22a. NAME OF RESPONSIBLE INDIVIDUAL L.A. Parnell	22b. TELEPHONE (include Area Code): 619-553-1588 22c. OFFICE SYMBOL: Code 634

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RTR STUDIES OF CLOSED COMBUSTION OF LIQUID METAL FUELS

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Abstract

The use of liquid metal combustion as a Rankine cycle heat source in stored chemical energy propulsion systems for undersea vehicles has fostered interest in the fundamental processes occurring during such combustion. This paper reports an investigation into the use of high energy, real-time radiography to provide X-ray images of the confined combustion of an oxidant injected and submerged in a fuel bath. Studies of the combustion processes and fluid dynamics of the jet-driven circulating flow in the fuel bath are described. Results of tests using cylindrical combustors which have single, horizontal oxidizer jets at their centerlines are presented. Selected radiographic images showing some of the large scale, low frequency turbulence, dense product behavior and reaction zone growth which occurs during such closed combustion processes are presented and discussed.

1. Introduction

Research and development efforts for undersea vehicles have for the past two decades been characterized by a continuing search for increased energy density in thermal power cycles.[1-4] One advanced propulsion system currently being developed includes the combustion of liquid alkaline metal fuels with halogenated oxidizers.[2-4] These sources of thermal energy are typically extremely reactive, release enormous quantities of heat in small spaces and operate at temperatures on the order of 1000 degrees Celsius, thus, investigation of the fundamental chemical, thermodynamic, and hydrodynamic processes therein necessitates the development and use of special diagnostic techniques.[5,6]

As these combustion characteristics represent a considerable challenge to experimental investigations, we have been developing methods of studying the internal processes in closed, liquid metal combustion through the use of penetrating X-ray radiation techniques, specifically real-time radiography (RTR). Continuous imaging of combustion processes which involve a jet of high molecular weight oxidizer immersed in a liquid Li fuel bath has been accomplished with both medium energy and high energy X-ray generators. Our efforts to date have focussed on (a) the region where the reactions occur and (b) study of the overall flowfield structure in the combustion chamber. Studies of the combustion zone have allowed us to obtain some information about its size, locus and stability, whereas examination of the entire confined flowfield has provided insights into the behavioral characteristics of the dense reaction products, mixing characteristics and interaction of the several phases during the combustion of the fuel.

2. Liquid Metal Fuel Combustion

Liquid metal combustion (LMC) for the high energy density heat sources of interest in this work makes use of molten metal fuels and high molecular weight oxidizers. Such processes have been described at length previously by Biermann[2], van der Sluys[3], Groff and Faeth[4] and others. Our purpose here is to report the investigation of diagnostic techniques which provide the opportunity for field studies of the reaction processes, hydrodynamics and transport processes which occur in such heat sources during the entire operation, ie from initiation of the reaction in a pure fuel bath to complete consumption of the fuel in a products-rich bath.

2.1 Reaction and Mixing in Closed Liquid Metal Combustion

Among features and phenomena of interest in the confined combustion process, the reaction zone is particularly important, especially when the reaction is highly exothermic, may involve vaporization of the fuel and may be governed by condensation. A considerable volume of work has been devoted to this aspect of the combustion of liquid metals, especially by Faeth and his co-workers.[7-11] What is in short supply in this technology is experimental data for very reactive closed combustion processes.

A second subject of study in these thermal energy sources is that of the mixing process within the closed combustion chamber and the interaction and effects of this mixing on the reaction, heat generation and transport processes. These considerations have an increasingly important effect on the combustor's performance as a heat source as the fuel is consumed. Our approach to the investigation of these phenomena is to endeavor to observe in real time the mixing in the entire chamber, recording dynamic images of the processes and then analizing the images to infer the mixing and transport characteristics throughout the observed field.

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2 Radiographic Considerations

Real-time radiography has been used as a non-destructive testing and inspection technique for the past three decades, during which time the technology and capabilities in this field have improved dramatically. There has been a corresponding broadening of the applications of this imaging technology to encompass many areas of diagnostic investigation due to the ability of this technique to disclose information about events inside hostile environments. RTR imaging requires a continuous penetrating radiation source, scintillating materials for conversion of the energy into visible light and appropriate optics and camera for recording the images. The physics of the image generation and factors which affect its quality are summarized by Rossi, et al.[13] A discussion of the application of real time neutron imaging to internal combustion processes is given by Jones, et al.[14] The issues of X-ray imaging of the closed combustion processes under consideration in the present work are discussed by Parnell, et al.[15]

3. Description of Experiments

In order to perform the experiments reported in this paper a test facility and some small combustors were designed and built at the Naval Ocean Systems Center. Several preliminary experiments were conducted to verify the combustor design, operation of the test equipment and thermal characteristics of the reaction process. Testing was then shifted to the Naval Weapons Center to gain access to existing radiography facilities.

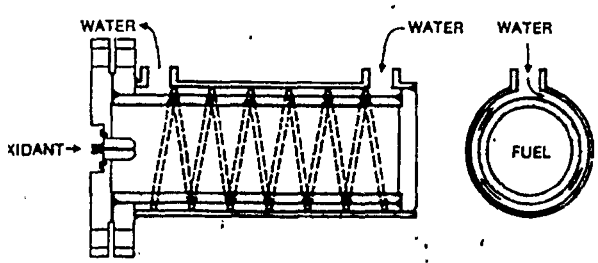

Fig. 1 Liquid metal combustor. Components as noted. Coolant flow paths are indicated.

3.1 Combustor Design

The first RTR tests used existing thick-walled cylindrical combustors designed to contain 0.82 kg Li, 0.20 kg pyrotechnic starting material, a pyrotechnic initiator, and sufficient ullage to minimize pressurization effects. Fig. 1 shows a cross-section of the design which consisted of two concentric stainless steel pipes, each 300 mm long. The inner pipe contained the lithium fuel, had an inside diameter of 92 mm and a wall thickness of 11 mm. This thick-walled containment was chosen to provide enough thermal resistance to prevent boiling of the cooling water. The outer pipe had a diameter of 130 mm and a wall thickness of 6.5 mm, leaving an annular space 6.5 mm thick between the two pipes. Prior to assembly of the two pipes a solid copper rod was helically wound around the inner one to force the cooling water to flow in a spiral path between the entry and exit ports in the outer pipe. The combustor and heat exchanger were completed by welding both of these pipes to a blind flange on one end and a 102 mm slip-on flange on the other. The mating flange for the latter contained the oxidant injector and appropriate fittings for evacuating the combustor and admitting initiator wires. A gasket of stainless steel and asbestos was clamped between the 102 mm flanges to prevent leakage of molten fuel, oxidant or reaction products.

After completion of the first RTR tests and analysis of the limiting factors in creating images of this combustion process with X rays,[15] it was evident that a medium energy X-ray generator was required to produce the images we desired. However, to use a medium energy machine it was necessary to reduce the X-ray cross section of the test apparatus. Consequently, the existing combustors were modified in two ways for use in subsequent tests: First, radiographic windows were cut in the outer pipe and aluminum was used to replace the steel to confine the cooling water. Secondly, the inside of the combustion chamber was bored to reduce the wall thickness to 5.5 mm. These changes resulted in a total steel thickness in the path of the X-ray beam of 11 mm, about one-third of that present before the modifications. Although these changes allowed the use of the medium energy machine, they did not permit observation of the entire combustion chamber nor allow use of an X-ray tube voltage which was low enough to provide the contrast required for real-time imaging of the reaction zone itself (ie, essentially a small void in the Li fuel). Thus, a small sacrificial plate was placed inside the combustor, mounted just in front of the injector and in line with the oxidizer jet. The purpose of this plate was to provide a dynamic indicator of the outline and growth rate of the reaction zone during the operation of the combustor.

3.2 Test Equipment and Facilities

The RTR tests were conducted in a test facility designed for testing large objects, such as rocket motors. The facility consisted of a concrete reinforced test bay and a control room located in a bunker about 200 meters away. A portable test stand was built to position the combustor in the proper location for the radiography and provide a means to connect the combustor instrumentation and control equipment to the control room (Fig. 2). The test stand also housed a self-contained oxidant delivery system that was controlled remotely to allow selection of one of two preset oxidant flowrates and a cooling water delivery system. During each test, temperature and pressure

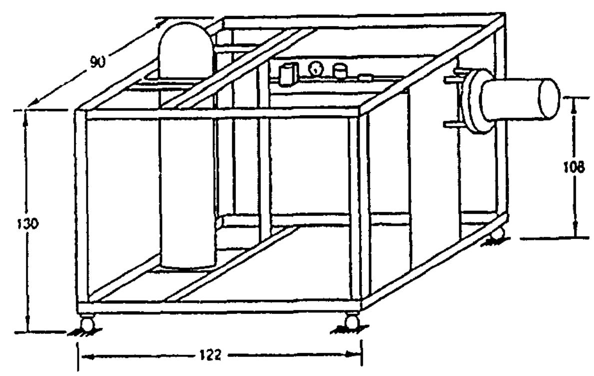

Fig. 2 Portable liquid metal combustion test frame.

data and video images were recorded while making the radiographic images. Data that was critical for control of the reaction was also displayed for the test conductor to monitor, including the Li bath and combustor wall temperatures, oxidant supply pressure, and the external video images.

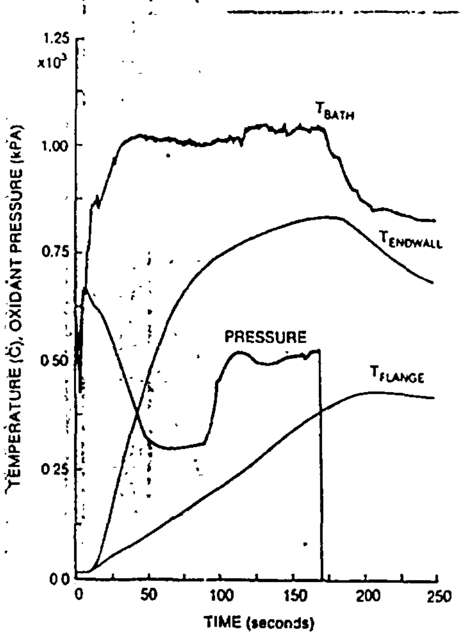

Fig. 3 Example of temperature and pressure histories during closed liquid metal combustion.

A sample of the data typically obtained for these experiments is presented in Fig. 3. Oxidant pressure was measured just upstream of the injector and is proportional to the mass flowrate. The oxidant supply line was overpressurized at the start of the reaction but became stabilized at the desired 0.30 kPa at t=60 s, during which time the bath temperature climbed to about 1000°C. For the test shown in Fig. 3 the oxidant pressure was increased to 0.50 kPa at t=90 s; the corresponding increase in flow resulted in a rise of only 50°C in bath temperature. The endwall temperature curve in the figure shows the response of the uncooled end of the combustor, a stainless steel plate 17 mm thick. The 102-mm flange was used to mount the combustor to the test stand; its temperature response reflects not only its large thermal mass but also the effect of fin cooling. Both of these ends of the combustor show peak temperatures (840°C and 420°C, respectively) occurring well after termination of the reaction.

3.3 Real-Time Radiography System

The X-ray system used for these LMC tests employed a 300 kVp continuous X-ray generator for the medium energy studies of the modified combustors and a 9 MeV radiographic accelerator for the high energy studies of the existing thick-walled combustors. The schematic shown in Fig. 4 shows the system's general configuration and components which, for the most part, are standard radiographic items. All the components were protected from a potentially hazardous environment, usually that of a solid rocket motor during static firing; the major environmental concerns were heat, vibration, acoustic noise and shock. The data was presented visually in real time on a video monitor and recorded as the tests were performed. Real-time viewing provided the project engineer with the opportunity to make immediate decisions regarding the tests during their progress. The image sizes could be varied from 5 cm x 5 cm to 90 cm x 102 cm. The standard 30 frames per second (FPS) video frame rate was used for all of these experiments. A system

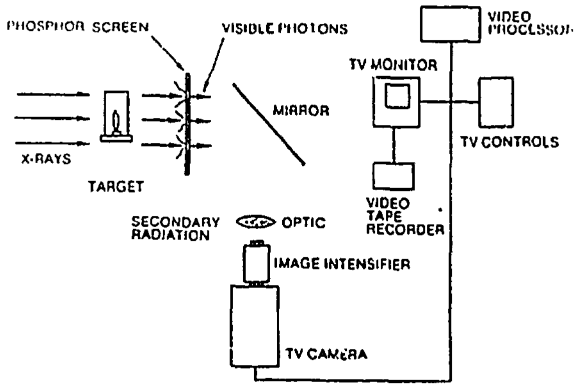

Fig. 4 Schematic of real time radiography test facility.

capable of 1000 FPS (full frame) is currently under development for high speed studies; the improved time resolution of this system would permit better understanding of the high speed events occurring inside liquid metal combustors and is planned to be used in future tests.

4. Dense Product Behavior

Separation of the dense reaction products into a product-rich immiscible fluid volume below the injection point is shown in Figs. 5-12. These radiographs were obtained using the high voltage linear accelerator described above. Growth of the volume of the dense products is discernable in the radiographs and is summarized in Fig. 13. Although the technique used to produce these photos does not permit identification of the turbulent structures in the combustion chamber, the low frequency components of such are seen in the video tape records. High frequency turbulence cannot be seen with standard frame rates. It is clear from the photographs and Fig. 13 that the dense product separation leaves a reduced volume for the highly chaotic fuel-rich region in which the turbulent mixing and combustion processes appear to be confined during the early stages of the fuel consumption. Significant mixing of the product volume is noted in the video records only after the reacting gaseous jet is engulfed by the products.

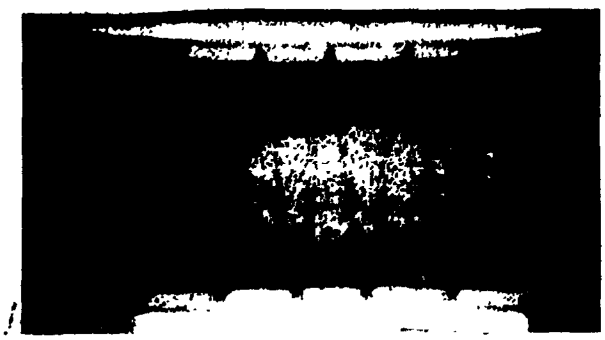

Fig. 5 Radiograph of closed LMC at initiation of reaction (t=0).

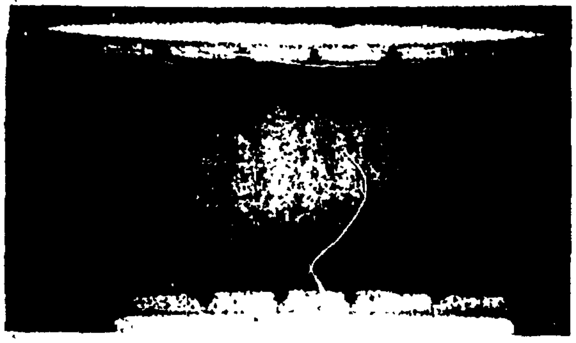

Fig. 6 Radiograph of closed LMC showing dense product paration at t=30 s.

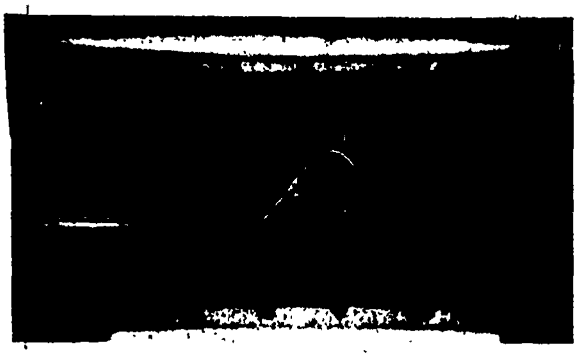

Fig. 7 Radiograph of closed LMC showing dense product separation at t=60 s.

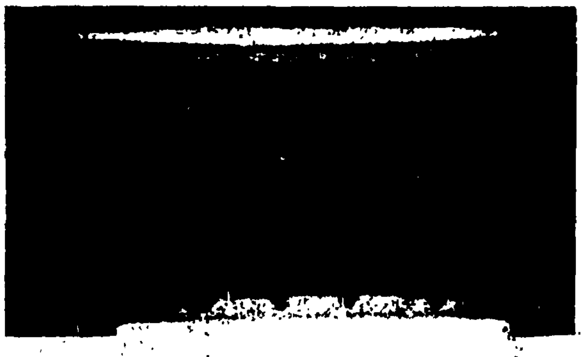

Fig. 8 Radiograph of closed LMC showing dense product eparation at t=90 s.

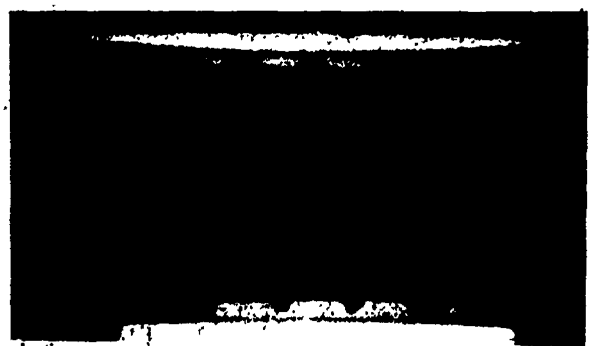

Fig. 9 Radiograph of closed LMC showing dense product eparation at t=120 s.

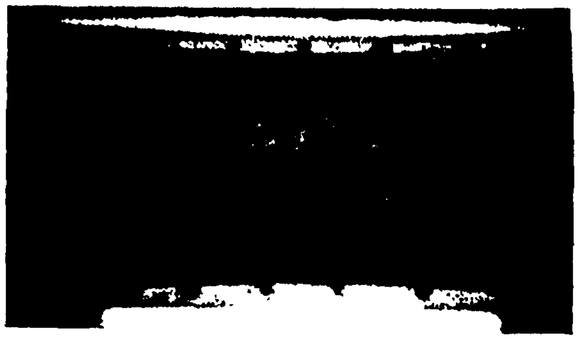

Fig. 10 Radiograph of closed LMC showing dense product separation at t=150 s.

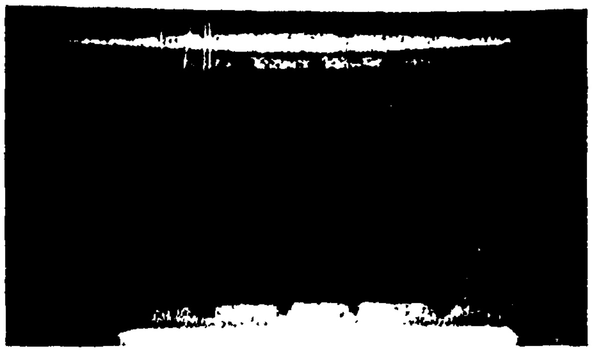

Fig. 11 Radiograph of closed LMC showing dense product separation at t=180 s.

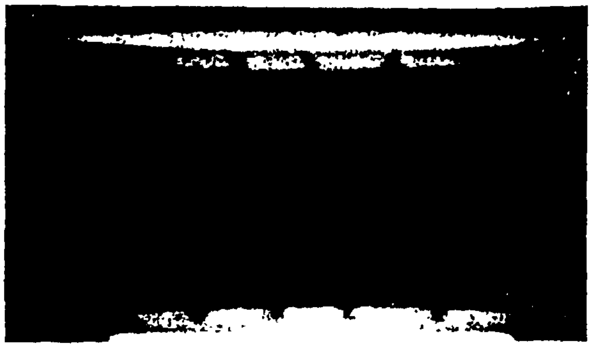

Fig. 12 Radiograph of closed LMC showing dense product separation at t=240 s.

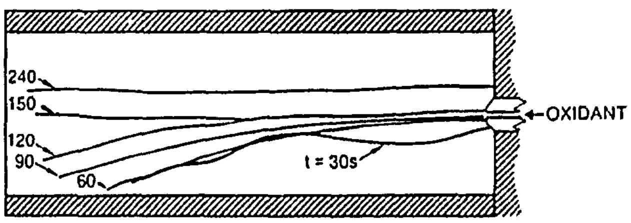

Fig 13 Summary of dense products volume growth characteristics during steady, closed combustion of liquid Li. Reaction elapsed times as indicated.

Reaction Zone Growth

The increase with time in the length of the reaction zone is dicated in Figs. 14-18. In these radiographs the center portion ' the sacrificial plate placed in the combustion chamber is seen be progressively destroyed by the extremely high-temperature action. A tungsten rod was also placed adjacent to the plate at e center of the combustor and is easily seen in all of the radio- aphs. It is offset from the axis of the oxidizer jet by the half- ickness of the sacrificial plate but nevertheless shows some fects of the reaction by bending downward, as seen in Fig. 18. nalysis of the growth rate and other characteristics of the reac- on zone will be published elsewhere.

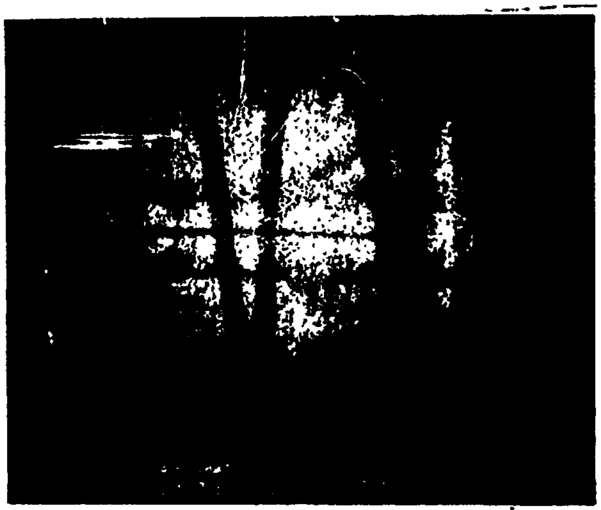

Fig. 14 Radiograph of combustor at initiation of reaction. iew through X-ray window showing drilled sacrificial plate id tungsten rod.

Fig. 15 Radiograph showing reaction zone effect on plate ter operating for 2 s.

Fig. 16 Radiograph showing reaction zone effect on plate after operating for 6 s.

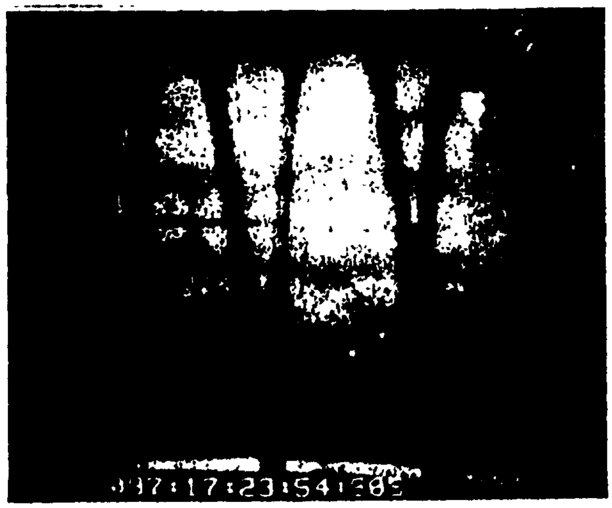

Fig. 17 Radiograph showing reaction zone effect on plate after operating for 16 s.

Fig. 18 Radiograph showing reaction zone effect on plate after operating for 22 s.

6. Concluding Remarks

Separation of a closed, liquid metal combustor's dense ·action products into a product-rich immiscible fluid region ›lume below the injection point has been observed and :scribed. This behavior has been a consistent feature of all of ıc LMC experiments conducted in the work reported here and ıs significant implications regarding the mixing and circulation ı such combustion. Evidence obtained from sacrificial probes laced in the path of the oxidizing jet indicate a stable reaction ›ne with a steady, quantifiable growth rate and a restricted en- :lope. These results demonstrate that studies of confined, very :active combustion processes at high temperatures can be per- ›rmed successfully through the use of real-time X-ray radiogra- hy, provided careful attention is paid to the requirements of ıc radiography in the combustor design and operation. This di- gnostic tool offers the opportunity to investigate dynamic ombustion processes and obtain quantitative as well as qualita- ·ve information.

Acknowledgements - This work was funded in part by the :aval Ocean Systems Center Independent Research Program and ı part by the Office of Naval Research.

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